Directional Guided Wave for Large Area Structural Health Monitoring
AFOSR Grant Number FA9550-06-1-0071 Final Report

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Executive Summary

The principal objective of this research project was the development of transducers for directional guided wave (GW) excitation and their application to monitor large structural areas by means of a radar-scanning technique. This research effort resulted in the production of one doctoral dissertation, a draft[1] of which is enclosed to this report (Appendix). The most significant advances and conclusions resulting from this work are presented in this executive summary.

The major contribution resulting from the research project is the design, fabrication, and testing of the Composite Long-range Variable-direction Emitting Radar (CLoVER) transducer, illustrated in Fig. 1. This device is composed of independent, directional piezocomposite sectors capable of efficiently exciting highly directional GW for structural inspection. By employing a radar-like scanning technique, where each segment is sequentially activated, the device is able to provide complete structural coverage (360° range) from a central location. A theoretical model based on 3-D elasticity was developed to characterize the GW excitation properties of the new transducer. In contrast to reduced structural theories, the developed model captures the multi-modal nature of GW at high frequencies (MHz-range). Furthermore, the flexibility of the theoretical framework enables the characterization of any transducer geometry. The theory was employed to guide the selection of the transducer dimensions and to gain insight into modal selectivity. This phenomenon occurs when the sensitivity to a specific GW mode is very weak due to the transducer dimension, thereby enhancing the purity of other GW modes. An important result from the theoretical development is the discovery that modal selectivity can only be obtained when using symmetric piezocomposite transducers, as illustrated in Fig. 2. Similarly, the theoretical model was used to determine the efficiency of the transducer relative to conventional configurations under similar electric inputs. This result is illustrated in Fig. 3 which shows that the CLoVER device can result in displacement amplitudes as large as eight times those obtained with circular piezoelectric wafers.

An alternative piezocomposite fabrication procedure was employed in this project, and the resulting transducers exhibited similar performance to conventional devices as shown in Fig. 4. An extensive experimental investigation was conducted to characterize the GW excitation characteristics of the in-house developed CLoVER transducers in isotropic and composite materials. Figure 5(a) illustrates the displacement pattern induced by a CLoVER sector in a metallic plate measured using laser vibrometry. A similar result produced with the theoretical model is shown in Fig. 5(b). The high directionality of the induced waves and the accuracy of the theoretical result can be readily appreciated. The propagation of GW in composite laminates is complicated by the anisotropy of the material. This results in the wave energy steering away from the direction in which the wave is launched. This phenomenon was systematically characterized

[1] The PhD defense is scheduled for October 9th, 2009 and the final document will be made public after that.

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14. ABSTRACT
The principal objective of this research project was the development of transducers for directional guided wave (GW) excitation and their application to monitor large structural areas by means of a radar-scanning technique. This research effort resulted in the production of one doctoral dissertation, which is enclosed with the final performance report. The major contributions resulting from this study are the design and analysis formulation, development of fabrication, and experimental tests of the Composite Long-range Variable-direction Emitting Radar (CLoVER) transducer. This new device is composed of independent, directional piezocomposite sectors capable of efficiently exciting highly directional GW for structural inspection. By employing a radar-like scanning technique, where each segment is sequentially activated, the device is able to provide complete structural coverage (360? range) from a central location.

15. SUBJECT TERMS
Structural health monitoring, guided-wave propagation, damage detection, directional transducer.

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for various composite laminates (unidirectional, cross-ply $[0/90]_{6S}$, and quasi-isotropic $[0/45/-45/90]_{4S}$) using CLoVER transducers. The steering effect can be appreciated for a unidirectional laminate in Fig. 6. Figure 6(a) shows the steering angle expected based on the slowness diagram (inverse of phase velocity) for the unidirectional laminate, while Fig. 6(b) shows the GW field excited by a CLoVER sector. The main result from the experimental tests was that, even though the steering effect influences the directional pulses excited by CLoVER transducers, using segments with azimuthal spans in the order of 20° can overcome this effect and provide complete structural coverage.

The performance of the proposed interrogation approach was experimentally assessed using simulated defects. Experiments were conducted in metallic and composite structures, and the results verified the damage detection ability of the devices as shown in Fig. 7. In this case, the damage was a through-thickness hole with a diameter of 5 mm. The largest reflection amplitude is observed when the sector directly aligned with the hole is activated, verifying the CLoVER ability to azimuthally localize defects. Further experiments were conducted in composite materials, aimed at assessing the influence of the steering effect on damage detection. In this case, the CLoVER sectors were used as directional sensors and it was found that steering did not significantly affect the damage detection and localization capability of the transducer.

The final development accomplished in this project was the development and characterization of a variable-length piezocomposite transducer. This novel device enables a significant degree of modal selectivity (up to 6 dB mode attenuation in the designed prototype), and is able to provide compensation for environmental effects. The unique electrode design (shown in Fig. 8) allows the activation of individual electrode finger segments, thereby enabling multiple transducer dimensions within a single, compact device. These dimensions are selected to maximize the transmission purity of specific modes using the theoretical model developed earlier in the project. An extensive set of experimental tests was conducted to characterize its performance, and these results are summarized in Fig. 9.

The people involved in this research effort at the University of Michigan were:

- Carlos E. S. Cesnik, PI
- Ken I. Salas, graduate research assistant (PhD candidate, expected degree 09 October 2009)
- Ajay Raghavan (PhD University of Michigan, 2007)

There were other people who also contributed to this work:

- Mark M. Derriso (AFRL)—provide insight into different Air Force needs and applications; context development.
- W. Keats Wilkie (JPL), Robert Bryant (NASA LaRC) and James W. High (NASA LaRC)—provided raw piezoelectric material and support on the manufacturing of piezocomposite elements.

The refereed journal publications resulting from this research are listed below:

- Salas, K.I. and Cesnik, C.E.S., “Guided wave structural health monitoring in composite materials using CLoVER transducers,” *Smart Materials and Structures* (in review).
- Salas, K.I. and Cesnik, C.E.S., “Design and characterization of a variable-length piezocomposite transducer for structural health monitoring,” *Journal of Intelligent Materials, Systems and Structures,* in press (12pp).
- Salas, K.I. and Cesnik, C.E.S., “Guided-wave excitation by a CLoVER transducer for structural health monitoring: theory and experiments,” *Smart Materials and Structures*, Vol. 18, July 2009 (27 pp).

- Salas, K.I. and Cesnik, C.E.S., "CLoVER: an alternative concept for damage interrogation in structural health monitoring systems," *Aeronautical Journal of Royal Aeronautical Society*, Vol. 113, Number 1144, pp. 339-356, June 2009.

The conference contributions stemming from this effort are listed below:

- Salas, K.I., Cesnik, C.E.S., and Lynch, J.P., "Guided-wave excitation in wind turbine structures using anisotropic piezo-fiber transducers," *Proceedings of the 7th International Workshop on Structural Health Monitoring*, Stanford CA, September 2009.
- Salas, K.I. and Cesnik, C.E.S., "Guided wave structural health monitoring using CLoVER transducers in composite plates," *Proceedings of the 50th AIAA/ASME/ASCE/AHS/ACS Structures, Structural Dynamics and Materials Conference*, Palm Springs CA, May 2009.
- Salas, K.I. and Cesnik, C.E.S., "Design of a Variable-length Piezocomposite transducer for structural health monitoring," *Proceedings of the 1st ASME Smart Materials, Adaptive Structures, and Intelligent Systems Conference*, Ellicott City MD, October 2008.
- Salas, K.I. and Cesnik, C.E.S., "Design, Characterization, and Modeling of the CLoVER Transducer for Structural Health Monitoring," *Proceedings of the 4th International Workshop on Structural Health Monitoring*, Krakow, Poland, July 2008.
- Salas, K.I. and Cesnik, C.E.S. "Guided Wave Experimentation using CLoVER Transducers for Structural Health Monitoring" *Proceedings of the 49th AIAA/ASME/ASCE/AHS/ACS Structures, Structural Dynamics and Materials Conference*, Paper AIAA-2008-1970 Schaumburg IL, April 2008.
- Salas, K.I. and Cesnik, C.E.S. "Design and Characterization of the CLoVER Transducer for Structural Health Monitoring," *Proceedings of the 16th SPIE Symposium on Smart Structures and Materials & NDT/ Health Monitoring*, San Diego CA, March 2008.
- Salas, K.I., Cesnik, C.E.S., and Raghavan, A. "Modeling of Wedge-shaped Anisotropic Piezocomposite Transducer for Guided Wave-based Structural Health Monitoring," *Proceedings of the 15th AIAA/ASME/AHS Adaptive Structures Conference*, Paper AIAA-2007-1723, Honolulu HI, April 2007.

FIGURES

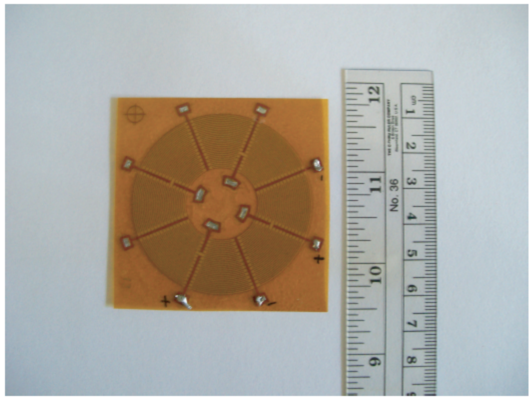

Fig. 1: Photograph of a CLoVER transducer prototype.

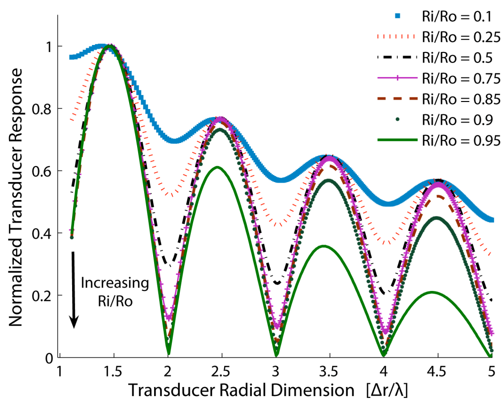

Fig. 2: CLoVER response as a function of transducer radial dimension: as the ratio of inner to outer radii (Ri/Ro) increases, the CLoVER sector approaches a symmetric rectangular geometry.

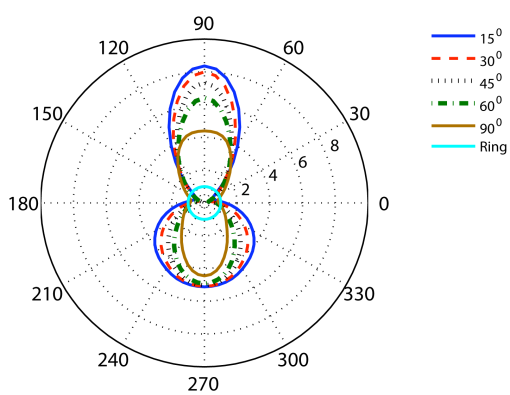

Fig. 3: CLoVER transducer offers increased displacement amplitudes relative to a similarly sized ring transducer for similar electric input (results normalized by the displacement amplitude for a ring geometry; transducer centerline along 90° direction).

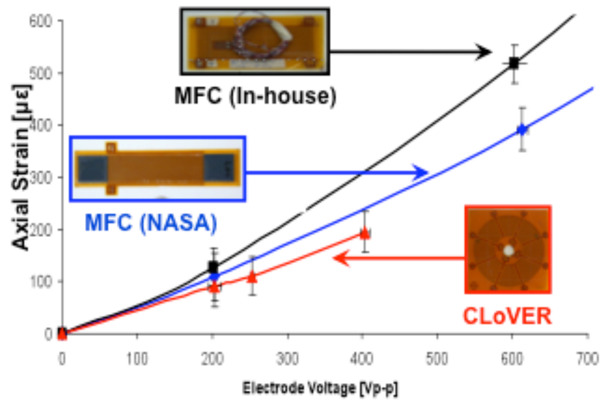

Fig. 4: Free-strain performance comparison between in-house and standard piezocomposite transducers (curved electrodes in CLoVER result in strain underestimate with directional gage).

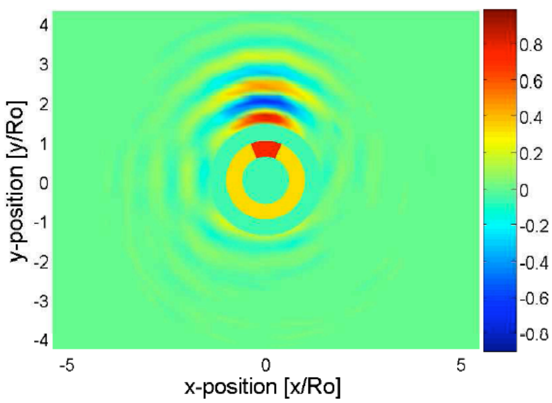

Fig. 5(a): GW field excited by a CLoVER sector (15 μs) in an Al plate at 210 kHz-mm measured through laser vibrometry.

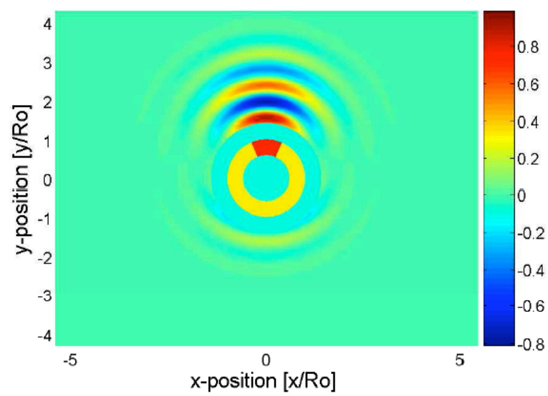

Fig. 5(b): GW field excited by a CLoVER sector (15 μs) in an Al plate at 210 kHz-mm calculated using the theoretical model.

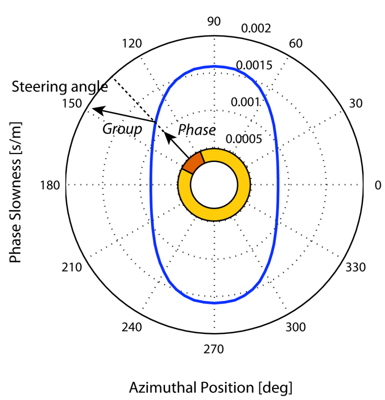

Fig. 6(a): Slowness diagram for unidirectional plate indicating steering angle when waves are launched at a direction of 45°.

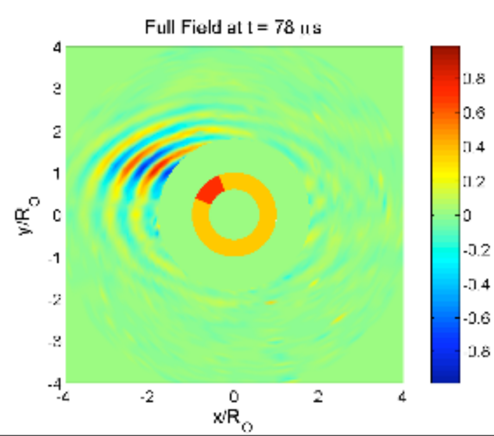

Fig. 6(b): GW field excited by a CLoVER transducer oriented 45° from the fiber direction in a unidirectional IM7/Cycom 977-3 laminate.

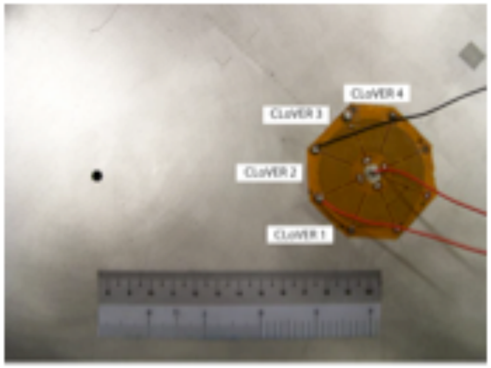

Fig. 7(a): Photograph of CLoVER transducer and simulated defect (5-mm hole).

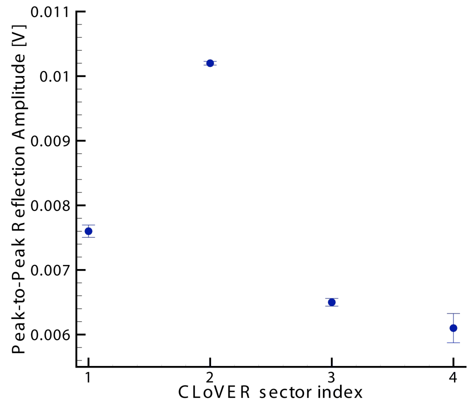

Fig. 7(b): Reflection amplitude for active CLoVER sectors (sector 2 aligned with hole).

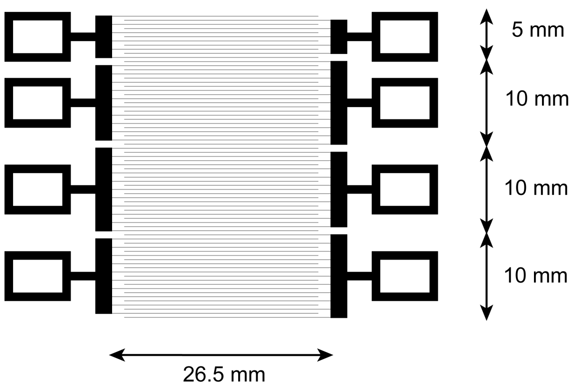

Fig. 8(a): Electrode design used in variable-length piezocomposite transducer where each segment can be independently activated.

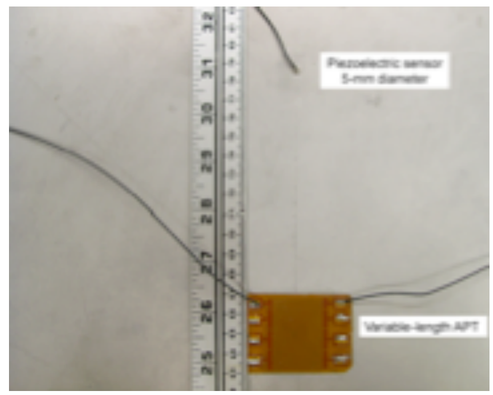

Fig. 8(b): Photograph of variable-length piezocomposite transducer bonded on aluminum plate for experimental testing.

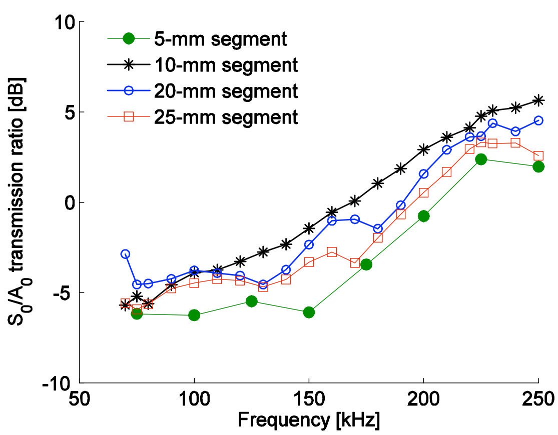

Fig. 9(a): Summary of symm./antisymm. mode transmission ratio.

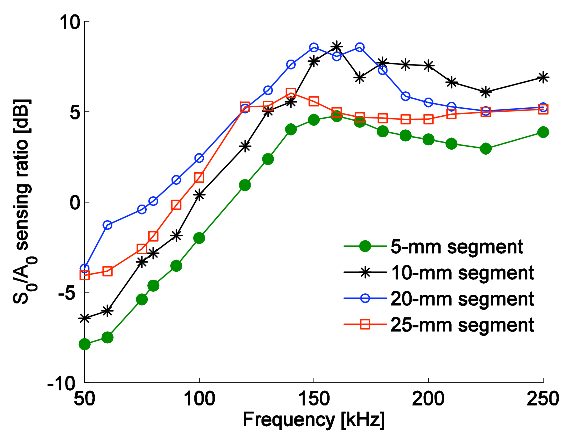

Fig. 9(b): Summary of symm./antisymm. mode sensing ratio.